THERMAL & FLUIDS ANALYSIS WORKSHOP
GSFC · 2015

Some General Principles in Cryogenic Design, Implementation, and Testing

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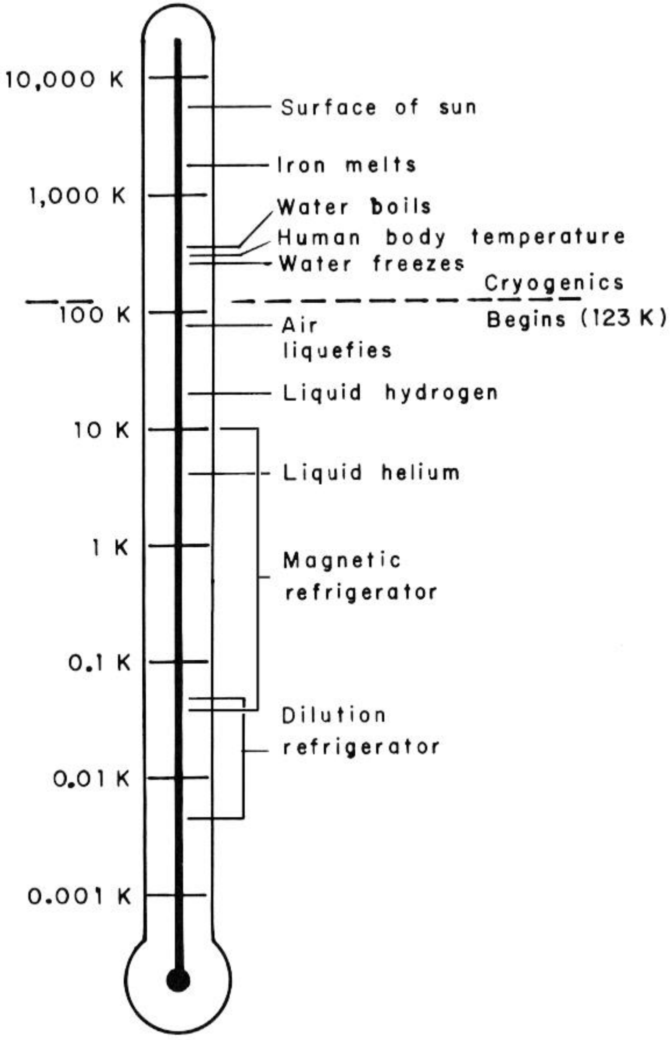
Outline

- Opening remarks
- The role of thermodynamics
- General design principles
- Properties of materials
- Producing “cold”
- Cryo-cooling in space
- Instrumentation
- Heat switches
- Superconductivity
- Cooling Below 1 K

What is “Cryogenic”

- For the purposes of this talk, T < 100 K is cryogenic
  - Air liquefies
  - Certain metals and ceramics become superconducting
  - Out of the realm of our normal experience (arctic conditions are not cryogenic)
  - Heat capacities decrease from the Dulong & Petit (3/2 R) value
  - In general the physics becomes different from room temperature

The Logarithmic Temperature Scale



- Note use of absolute scale
- Each decade corresponds to different physics and different solutions to design problems
  - 100-1000 K is the range we are used to
  - 10-100 K, air liquefies and solidifies, High temperature superconductivity
  - 1-10 K, low temperature superconductivity, liquid helium
- Note that properties are not “constant” any more, so concepts like “average” temperature must take this into account
- When analyzing a system, heat flow margin will take the place of temperature margin

Thermomdynamics is a Serious Subject!

The Laws of Thermodynamics

- First Law of Thermodynamics (Conservation of Energy)
  - Energy in = Work out
  - you can't get something for nothing

- Second Law of Thermodynamics (Entropy)
  - ∂Entropy ≥ (∂Energy/Temperature)
  - you can't break even

- Third Law of Thermodynamics (Absolute Zero)
  - Entropy -> 0 as Absolute Temperature -> 0
  - there's no use trying

Thermodynamics

- Thermodynamics is key to understanding cryogenic processes
- Refrigeration
  - 1st and 2nd laws of thermodynamics
- Approach to Absolute Zero
  - 3rd law of thermodynamics

Staging

- Intercept heat in stages to reject heat at the highest possible temperature
- In general heat rejection difficulty goes as T^{-2}

Design: The “KISS” Principle

- Start with a design that can be calculated using “back of the envelope” methods
  - Make all components easy to analyze
    - Analysis effort should not be underestimated!
  - The fewer items that are crucial in a design the better
    - Simpler analysis
    - Simpler construction
    - Simpler validation

Example

- GSE motor driven photogrammetry cameras for JWST
  - Original concept: camera housing to cool passively through incidental contact in motor and gears
    - Very difficult to model and verify performance
    - Became an extra potential heat source that had to be tracked
  - Solution: make system “deterministic” by using thermal straps

Estimating by Previous Example

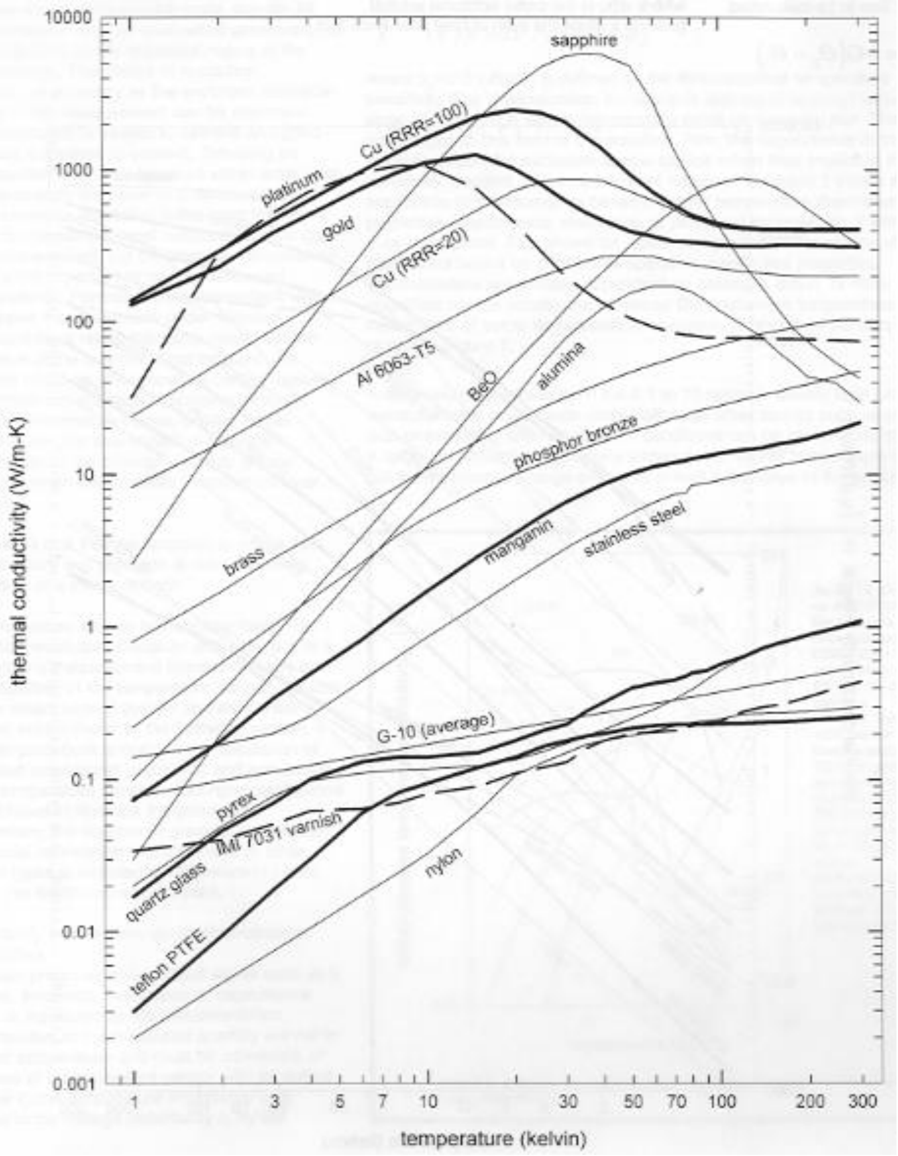
- Previous systems have been made that can be used as a “jumping off” point for a thermal design or estimating cooling requirements
  – Various parametrizations have been used to give an analog expression to these extrapolations or interpolations of actual systems

Properties of Materials

- Thermal Conductivity
- Thermal Absorptivity and Emissivity
- Strength and Brittleness Properties
- Electrical Conductivity
- Specific Heat
- Gases and Liquids (density & pressure vs. temperature, heat of vaporization and melting, crystal structure, etc.)
  - Example: solid nitrogen has a low temperature change of phase which causes an expansion. This was learned by NICMOS at the cost of a compromised mission

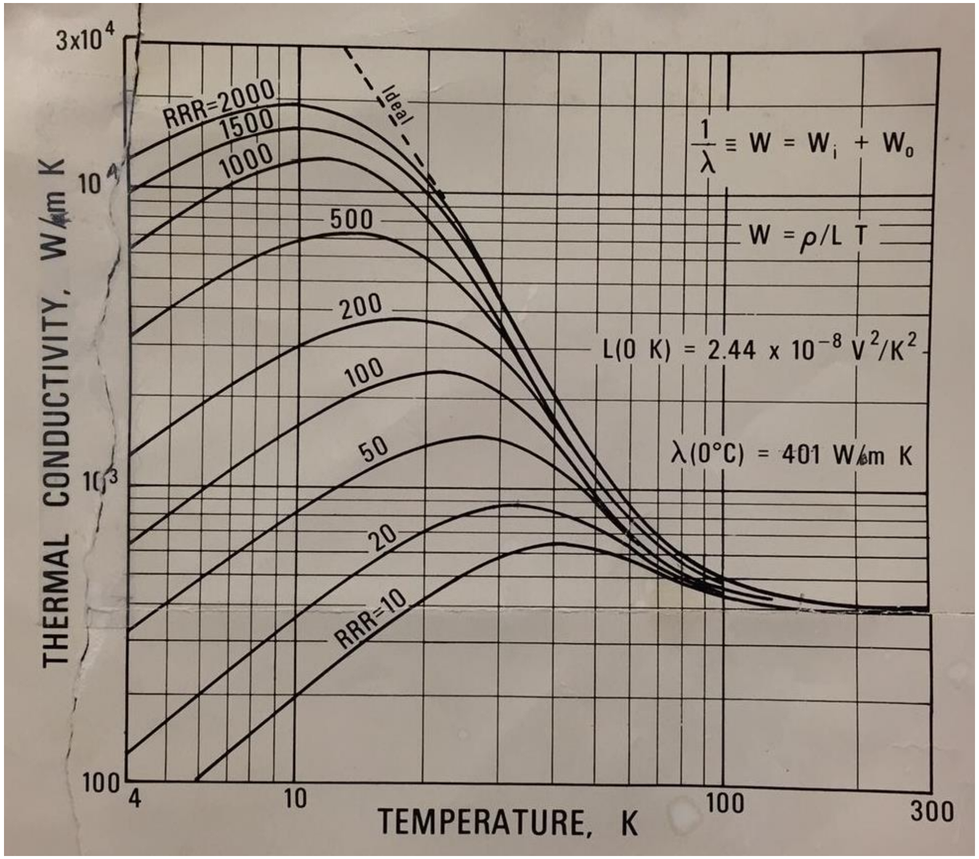
Conductivity Graph

- Thermal conductivity varies greatly between room T and low T



High Purity Metals

- At low temperature electrons have fewer phonons to scatter from, so the thermal conductivity goes up until defects and impurities dominate



RRR = residual resistance ratio
A measure of the purity of the metal
And its crystallinity

Wiedemann-Franz

- Electrons carry the heat in metals
- W-F is a relation between electrical and thermal conductivity

  $\rho = L_0 T/K$

  Where ρ = resistivity, T = absolute temperature, K = thermal conductivity, and L_0 = Lorentz constant = $2.44 \times 10^{-8}\ V^2/K^2$
- Not applicable to superconductors

Emissivity and Absorptivity: Temp. and Wavelength Dependence

- The emissivity of most materials is temperature and wavelength dependent
  - Requires wavelength dependent analysis for radiation which is usually accomplished by creating a few wavelength bands in the analysis software
  - Experience on JWST shows that 3 wavelength bands representing the major “hot” (60 K < “hot” < 300 K) sources provide enough accuracy without greatly increasing model run time

Properties of MLI

- The Lockheed Equation

$$Q/A = [(C_s N^{3.56} T_m)/(N_s+1)](T_h-T_c) + [(C_r \varepsilon_{tr})/N_s](T_h^{4.67}-T_c^{4.67})$$

Where Q/A is W/m^2, Tm is the average of T_h and T_c, N is the layer density in layers per cm, N_s is the total number of layers, ε_{tr} is the surface emissivity, C_s is 2.11e-9, and C_r is 5.39e-10.

- Degradation of MLI at lower T
  - Basically dominated by thru-layer conduction at low T
- Structural MLI
  - Each layer is separated by a well defined spacing and has some structural qualities
- Lateral conduction
  - May be minimized by slitting

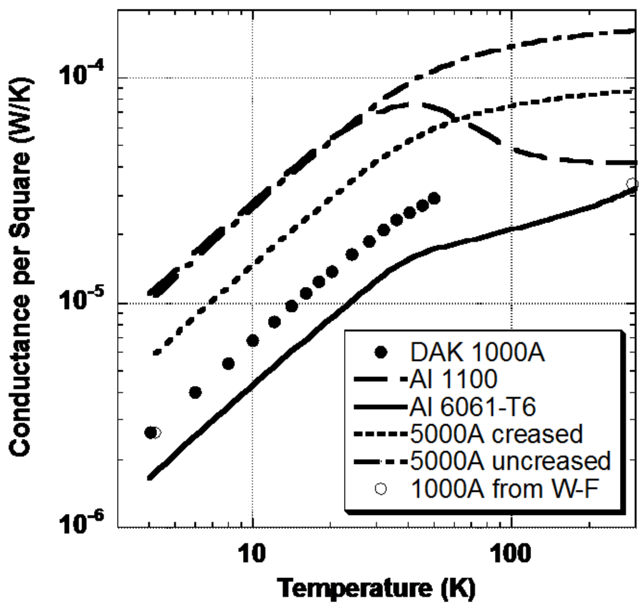
DAK Emissivity vs. T

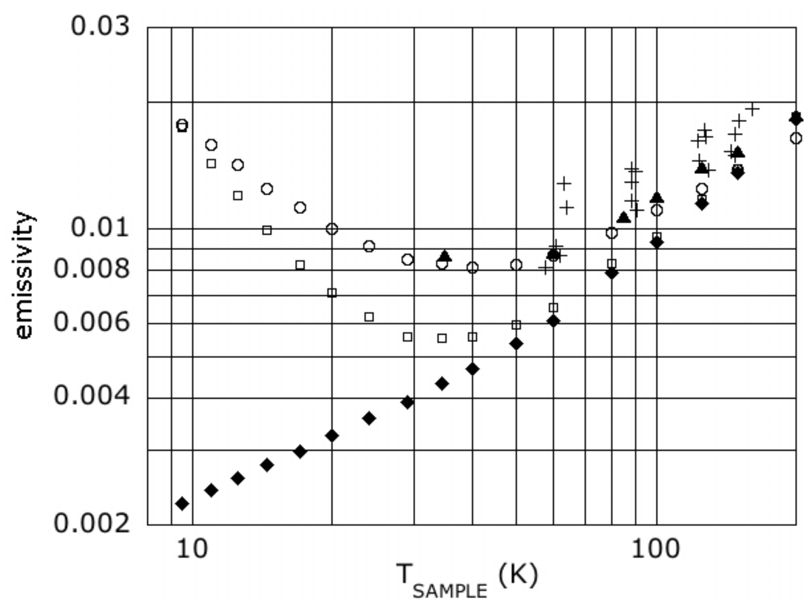
Metals' emissivity follow the Hagen-Reubens relation to first order:

$$R \sim 1-2[(2\varepsilon_0\omega)/\sigma]^{0.5}$$

R is the reflectivity, ε_0 is the permitivity of vacuum, ω is the frequency of the radiation and σ is the conductivity of the metal surface

But DAK's metal is thin





Suitable Materials for Cryo

- Austenitic stainless steels: 304, 304L, 316, 321, A286
- Aluminum alloys: 6061, 6063, 5083, 2219, 1100
- Copper: OFHC, ETP and phosphorous deoxidized
- Brass
- Fiber reinforced plastics: G –10 and G –11, CFRP
- Niobium & Titanium (frequently used in superconducting RF systems)
- Invar (Ni /Fe alloy)
- Indium (used as an O ring material)
- Kapton and Mylar (used in Multilayer Insulation and as electrical insulation
- Teflon (does not become brittle, but creeps)
- Quartz (used in windows)

Unsuitable Materials for Cryo

- Martensitic stainless steels - Undergoes ductile to brittle transition when cooled down.
- Cast Iron – also becomes brittle
- Carbon steels – also become brittle. Sometimes used in 300 K vacuum vessels but care must be taken that breaks in cryogenic lines do not cause the vacuum vessels to cool down and fail
- Rubber and most plastics
  - Plastic insulated wires are frequently OK as long as the wire is not repeatedly flexed which could lead to cracking of the insulation (check outgassing first)

Gas Conduction-1

- Can be bad
  - Unwanted thermal shorts in a test
  - Failure of the XRS instrument on Astro-E2
- Can be good
  - Gas gap heat switches
  - Aid to speed cool down and warm up
  - Can be used as a substitute for a failed heat switch

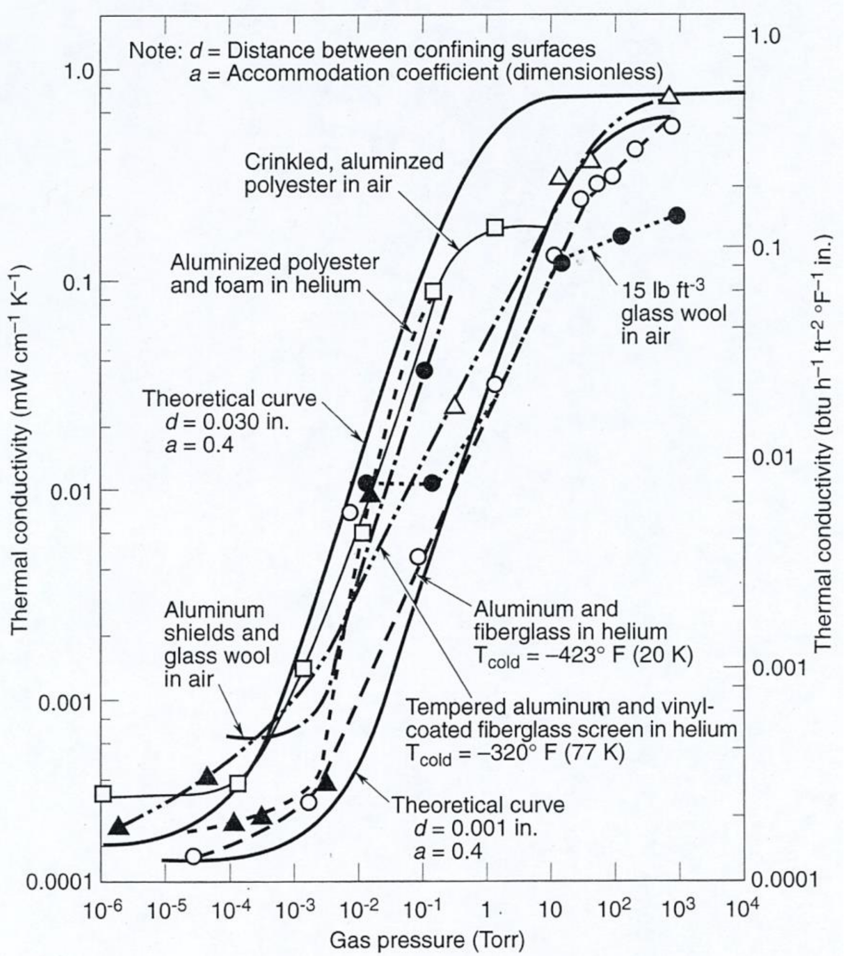


Fig. 5.2. Effect of gas pressure on thermal conductivity.

Gas Conduction-2

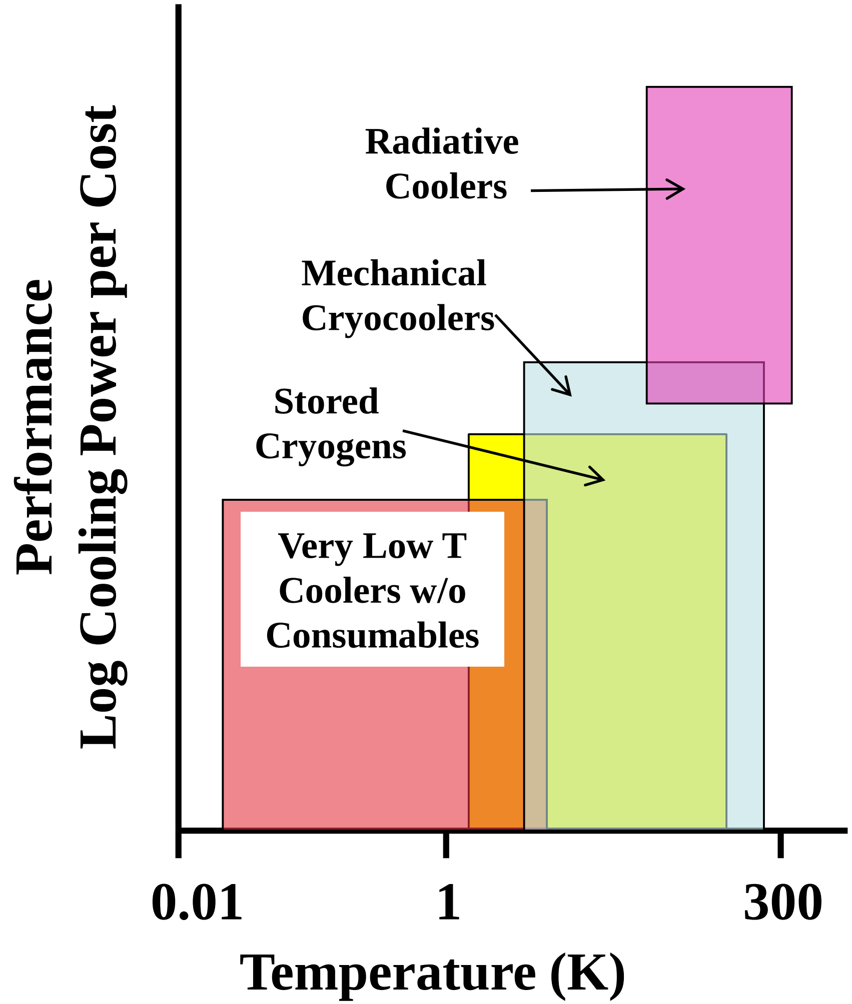
- Molecular Heat Transfer
  - Gas density is lower than mean free path between objects
  - Heat transfer depends on the temperature difference but not on the separation distance
- JWST example
  - To shorten the cool down time from room T (300 K) to 30 K helium exchange gas is used (~10^{-2} Pa) within the chamber
    - Mean free path is exceeded for 10^{-3} to 100 Pa depending on objects' spacing
- ASTRO-H example
  - In the EM dewar a heat switch failed open
  - To operate the adiabatic demagnetization refrigerator, a method to use ~10^{-3} Pa of gaseous helium to remove the heat of magnetization was used successfully
    - Too much gas causes excessive thermal shorting to warmer components in the dewar

Producing Cold: Cryogens and Cryocoolers

- Mechanical cryocoolers
- LN_2, LHe, etc.
- Supplement through use of intermediate cooling stages
  - Vapor cooling
  - radiators

Producing Low Temperatures in Space

- Radiation can only work to ~ 30 K, practically

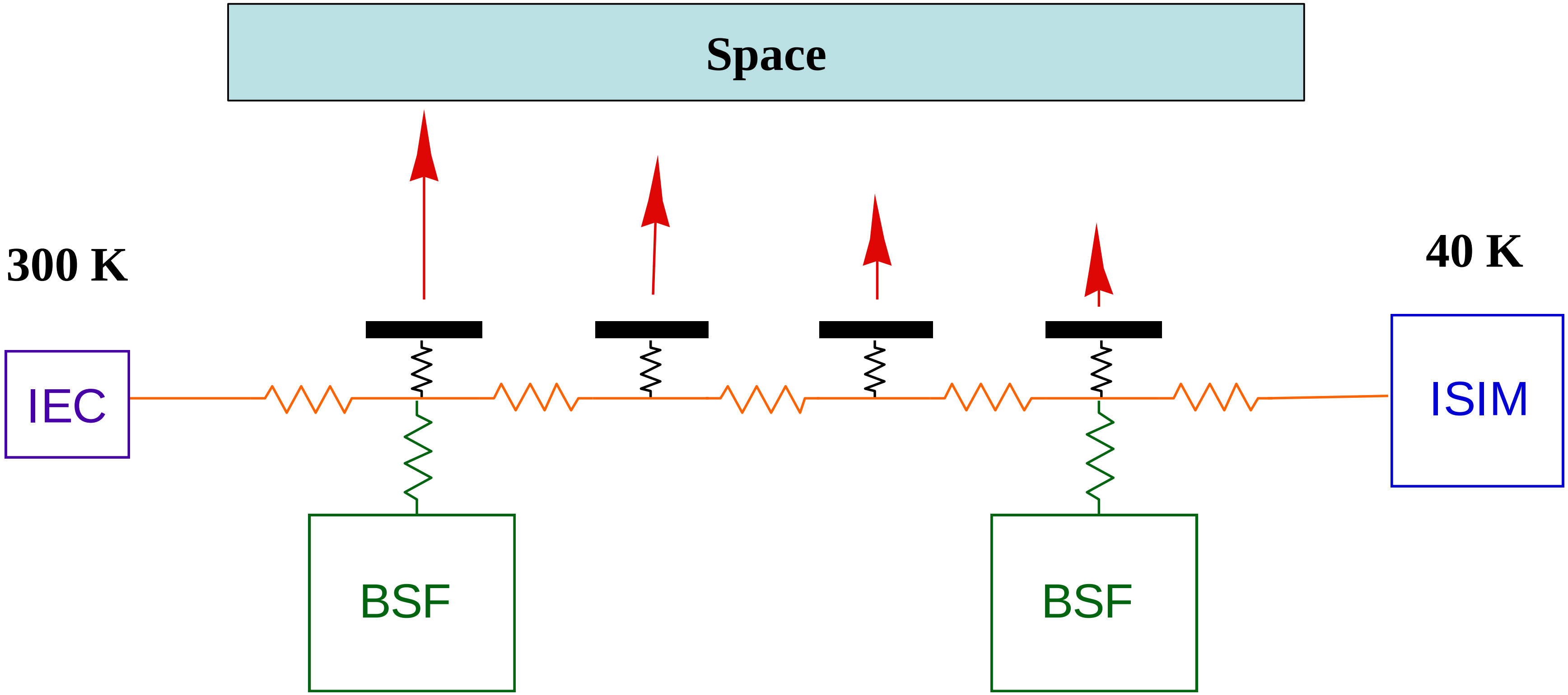


Radiators in Space

- Some flight heritage at cryogenic temperatures (COBE, Landsat, Cassini/CIRS, MAP, Spitzer)
  – JWST will use radiative cooling
  – Successful test of Subscale Cryo-optical Thermal Testbed in support of ST-9 Large Space Telescope proposal
- Operate from room temperature (and above) to as low as 30 K
  – Depends strongly on mission design
- Passive heat rejection
  – Sunshade/earthshade provides shielding from incoming radiation
  – Radiator with a view of deep space connects to heat source (instrument, optics, part of spacecraft bus) by means of a thermal distribution system
    - Metal conductors
    - Loop heat pipes
  – Requires heaters/thermostats to regulate temperature
- Require stringent controls to meeting thermal budgets
- Spitzer reached 34 K on radiative outer shell
- JWST expects to reach ~26 K on instrument radiators

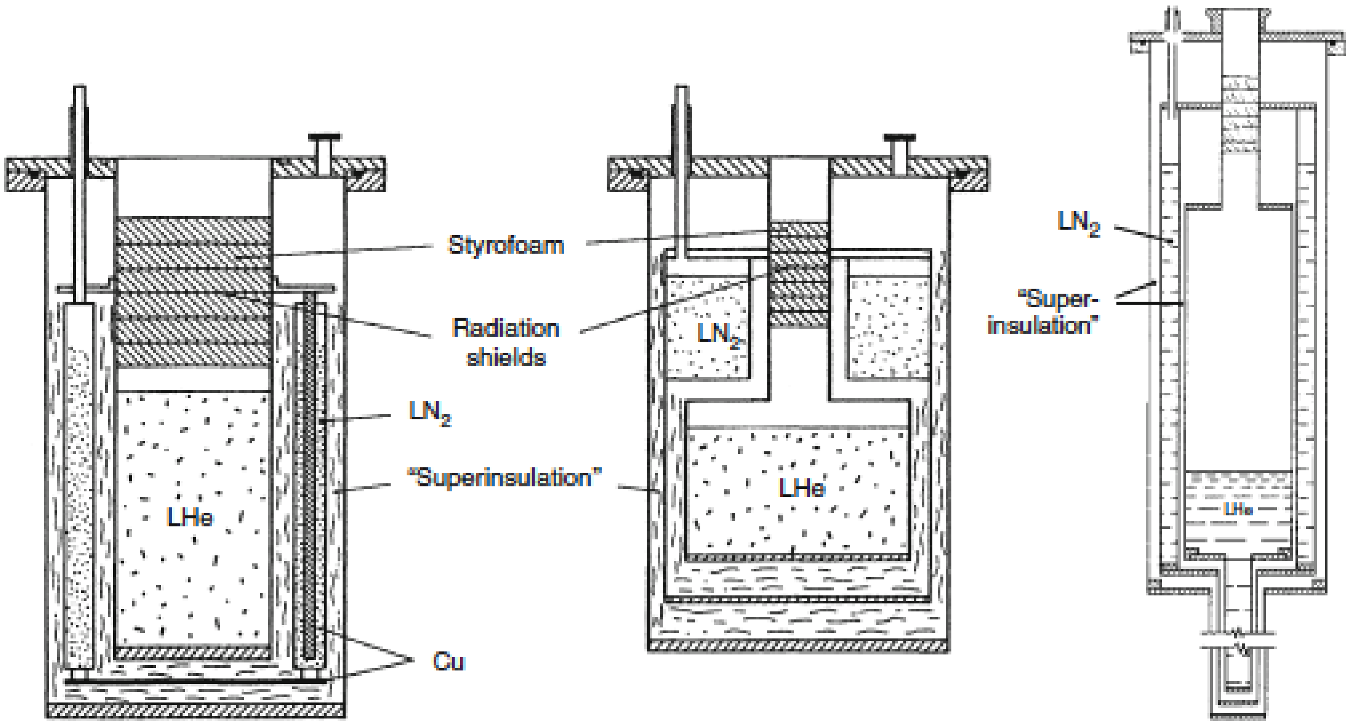
Different Geometry - JWST Harness Radiator

- 4 stages of isolation to limit the amount of heat flowing from the room temperature electronics (IEC) to the cold instruments (ISIM)
  - Coldest stage is actually only isolator



Dewar Construction

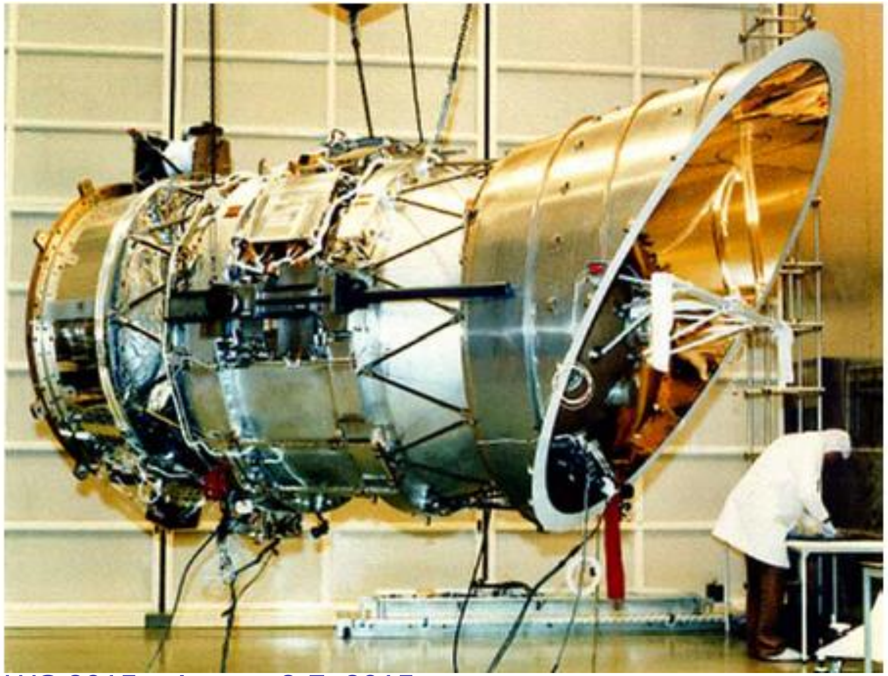
- Dewar must trade mechanical robustness with thermal isolation
- For liquid helium dewars usually have conduction and radiation heat loads roughly the same
- Use vapor cooled shields to intercept heat at higher temperatures



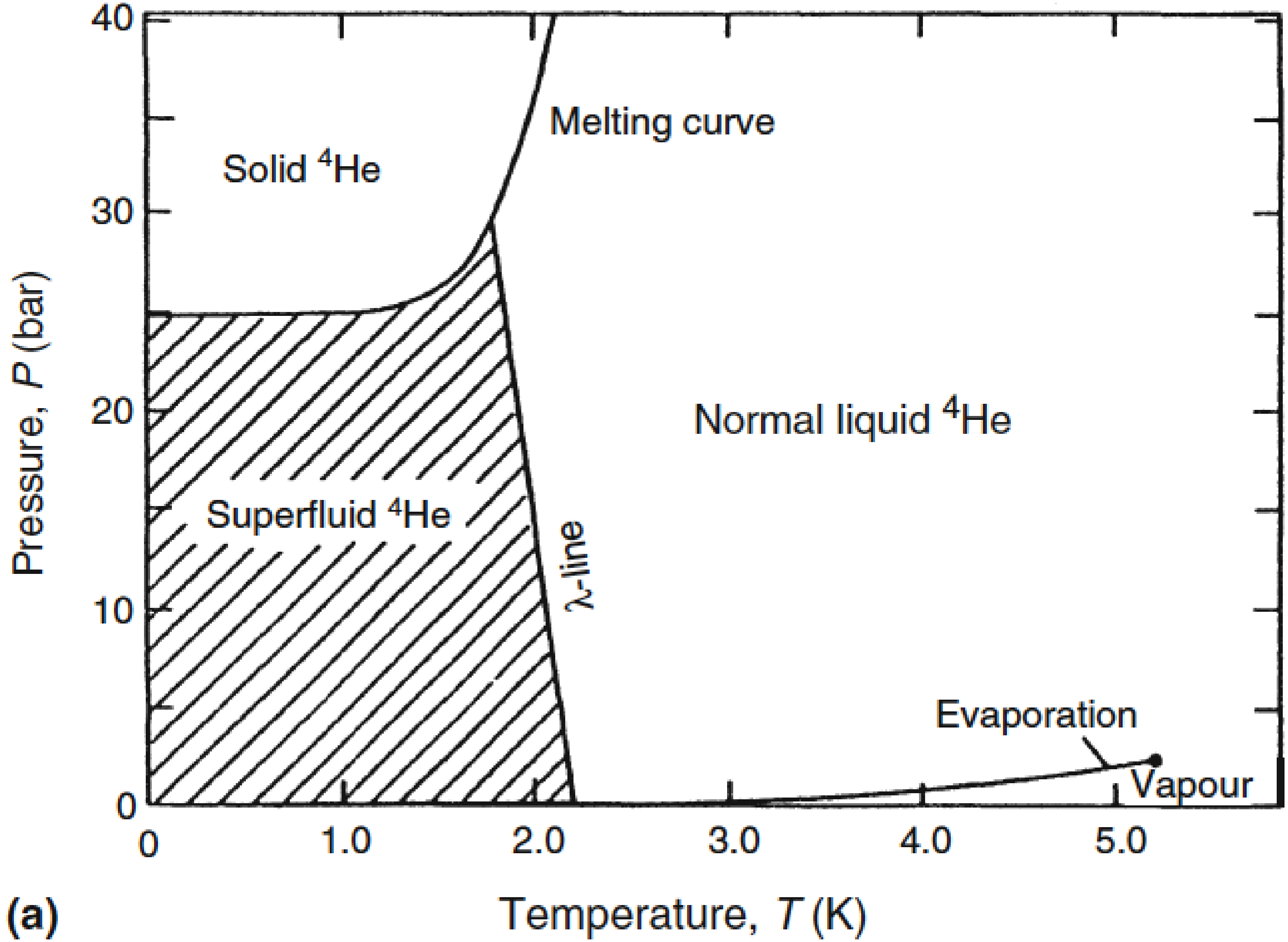
Working with Cryogenic Fluids

- In general:
  - Low heat of vaporization
  - Can be pumped or pressurized to change boiling point
  - Can freeze if too cold (except helium)
  - Low to zero contact angle, i.e., wets all surfaces
  - Represents a large potential energy in a sealed container

IRAS Dewar Launched 1983
First Superfluid He Dewar in Space
(not as large as it appears)



The Unique Phase Diagram of ^{4}He



Lab Cooler - Gifford McMahon Cycle

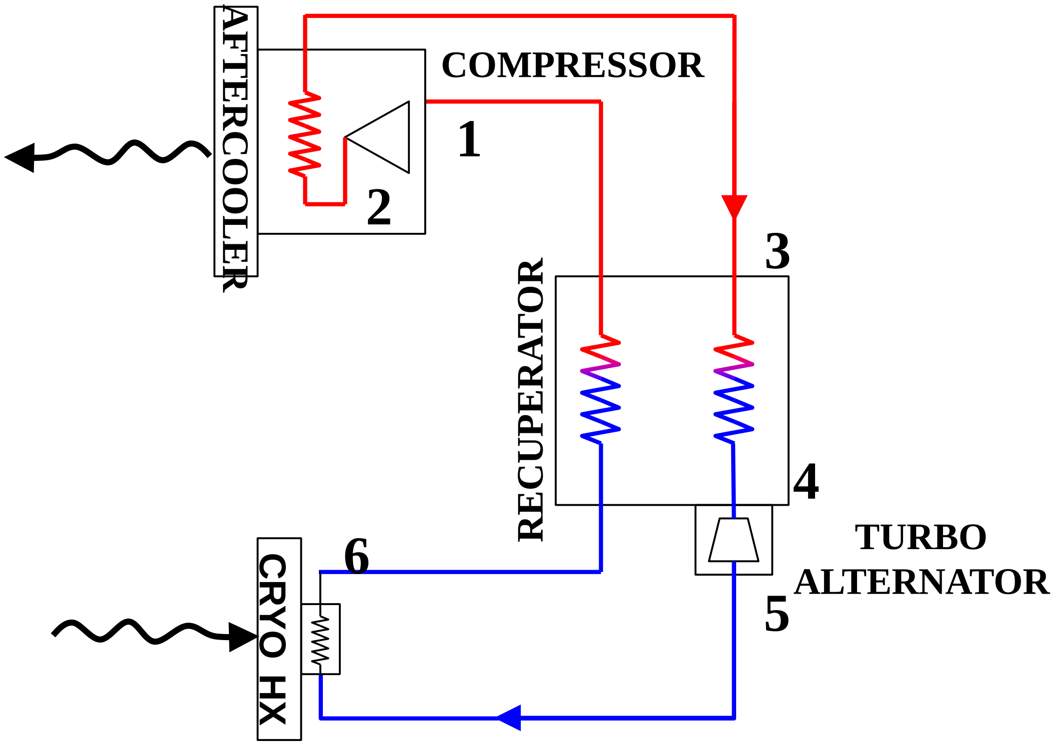
- Gifford-McMahon Refrigeration Cycle
  - Regenerator stores heat in compression phase, and releases heat in expansion phase
  - Compress while most of the gas is at warm end, and expand while most of the gas is at the cold end
  - Reverse the phase, and you have an expensive heater!

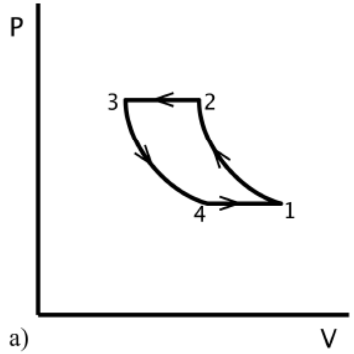
Cryocoolers for Space Use

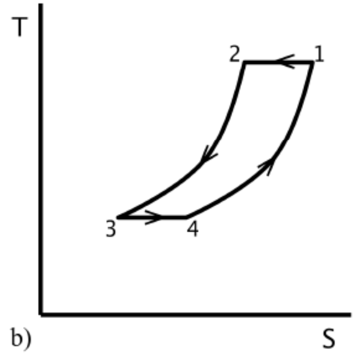
- Mass, size, input power, and reliability are drivers
- Reverse Brayton Cycle
- Stirling Cycle
- Pulse Tubes
- Joule/Thomson Coolers

Reverse Brayton Cycle

Turbo alternator removes work from cold stage, therefore increasing cooling

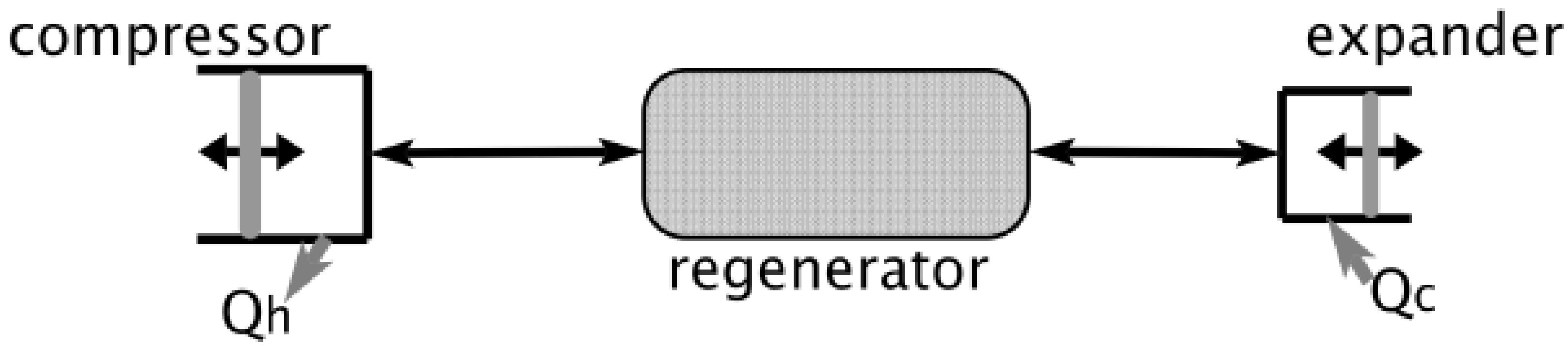


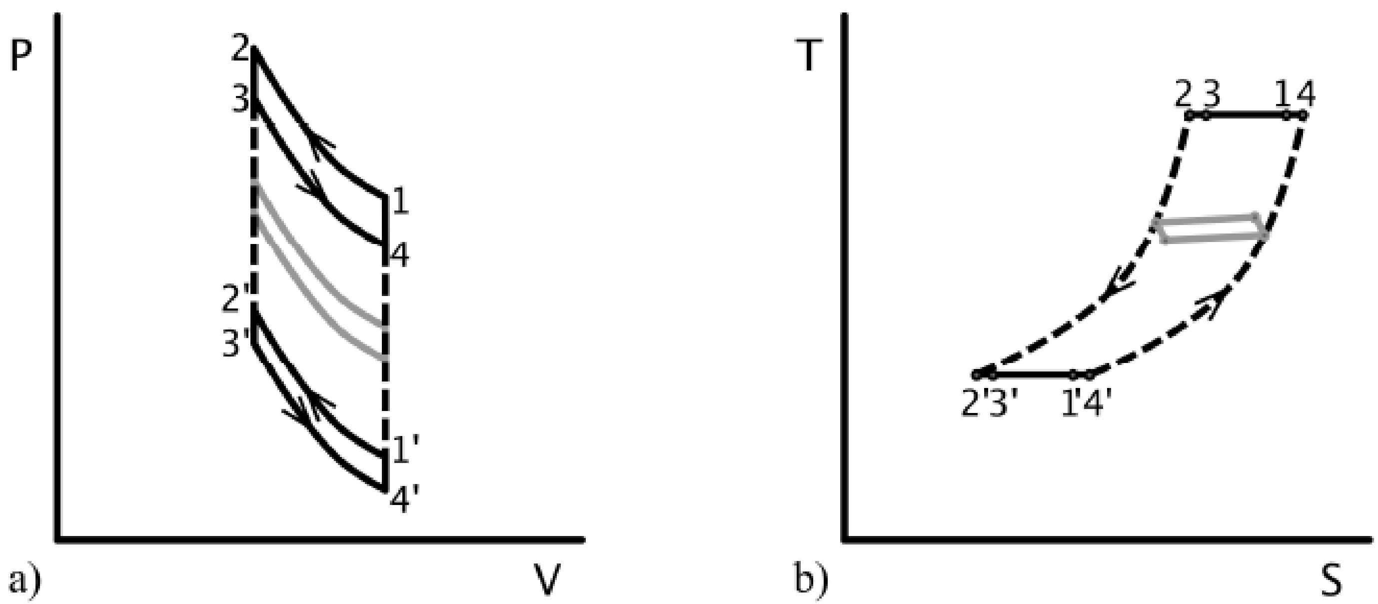




Regenerator Cycle (Stirling and Pulse Tube)

From P. Kittel, "Are P-V and T-S Diagrams Meaningful for Regenerative Coolers?"



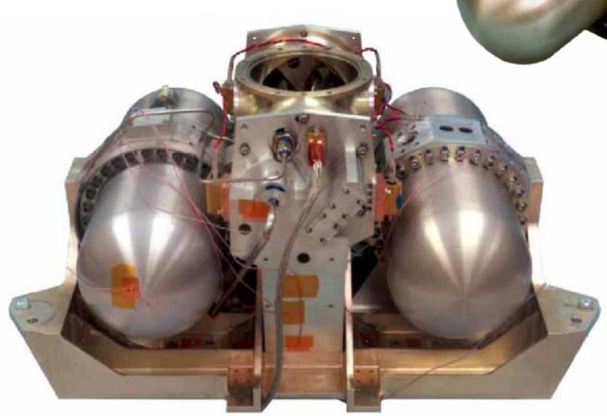


Stirling Cycle

- Similar to GM cycle
  - Identical function of regenerator in coldfinger
  - Pressure cycle driven by oscillator rather than tanks, valves and a compressor
  - Phase angle controlled electrically, mechanically, or pneumatically
- Easier to miniaturize than GM

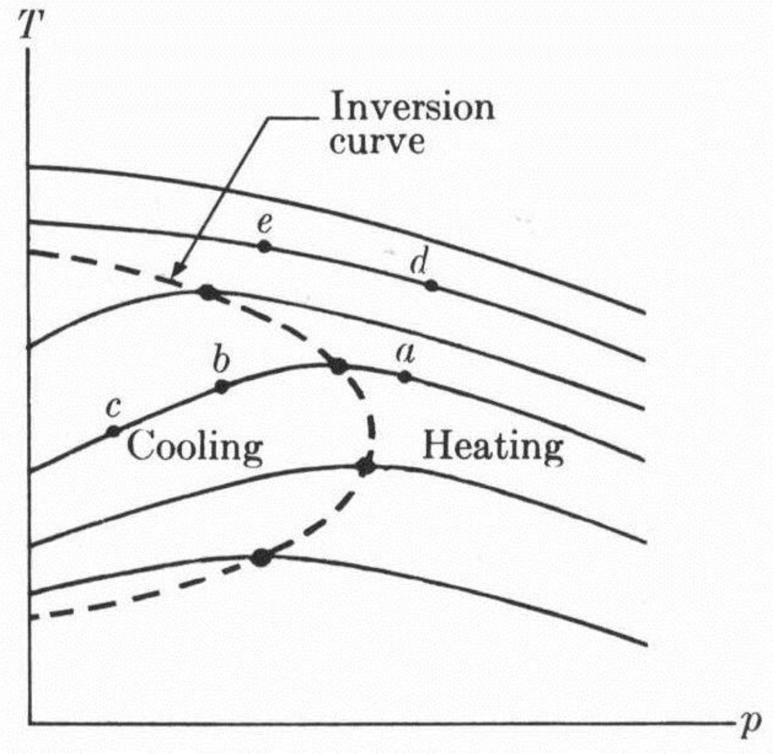
Pulse Tubes

- Similar to Stirling cycle
  - Identical function of regenerator in coldfinger, pressure cycle driven by oscillator
  - Phase angle controlled by resonant gas volume
  - Simpler <u>mechanism</u> than Stirling, but a whole new set of gas-control challenges

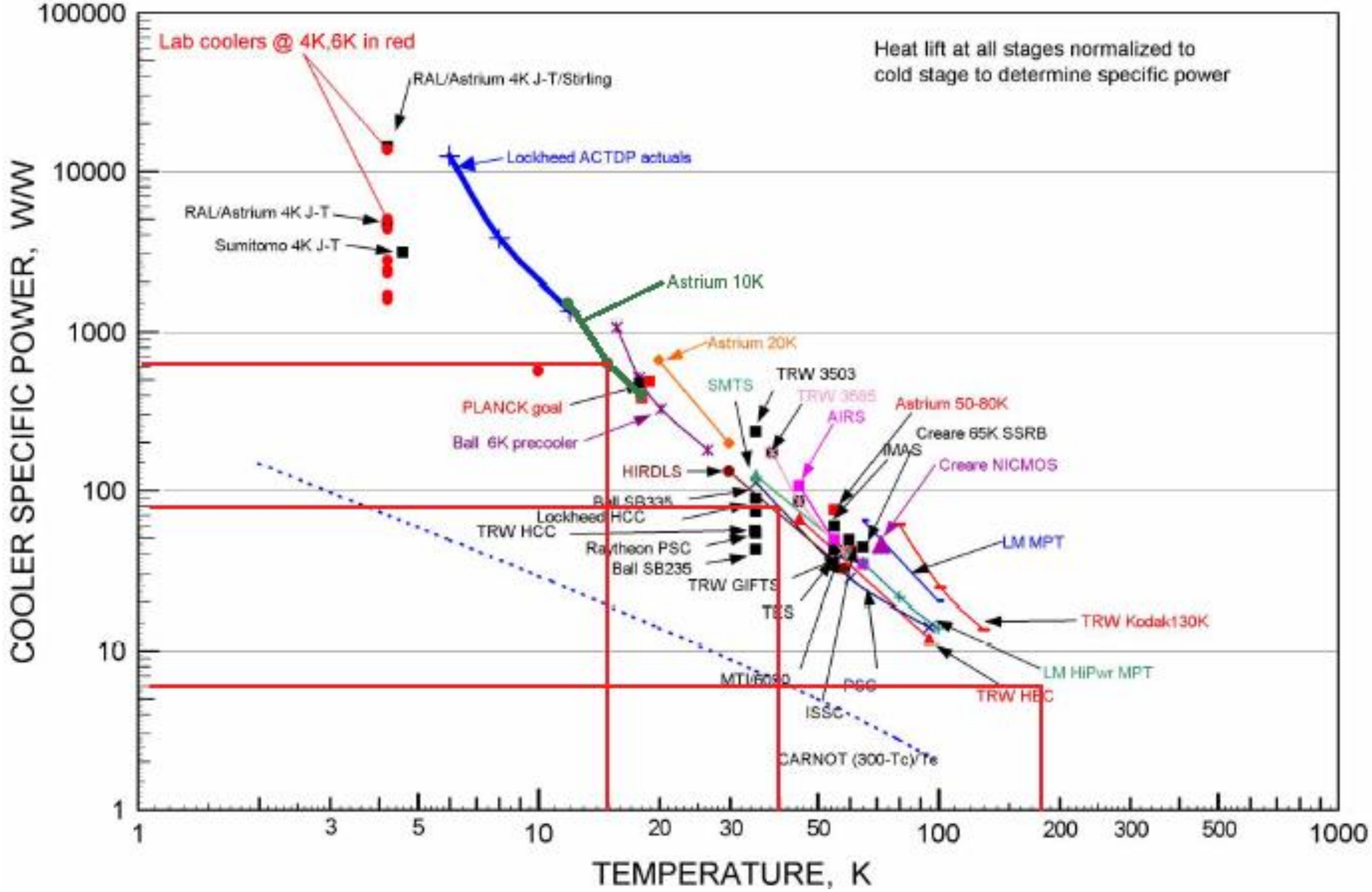


Joule Thomson Expansion

- Gas must be precooled and not too high in pressure to produce cooling when expanded isenthalpically



Space Cryocooler Performance



- Roughly T^{-2} dependence on input power to cooling power ratio

Instrumentation and What is Important to Measure

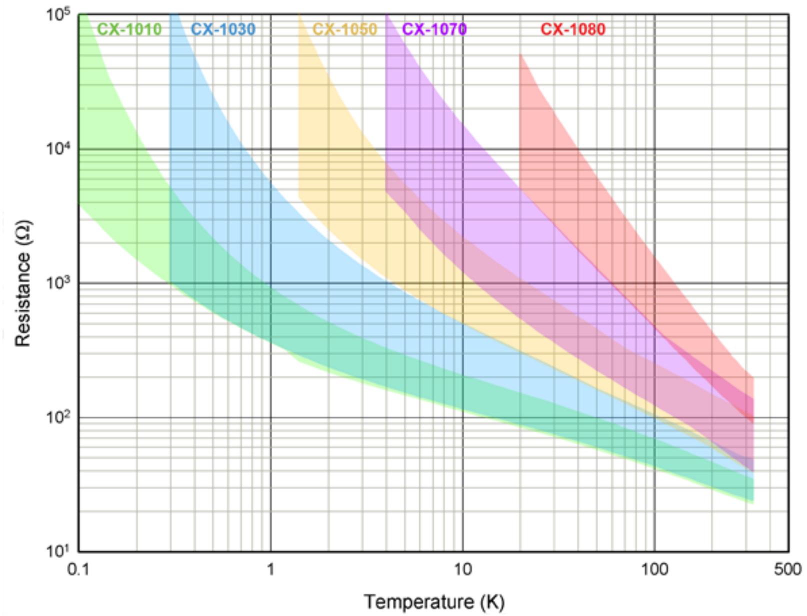
- Thermometry, thermometry, thermometry
- Pressure for fluids
  - May be in situ or reading vapor pressure
- Pressure for vacuum
  - Pressure reading depends on temperature
    - $P_A = P_B (T_A/T_B)^{1/2}$
  - For example a pressure gauge on the vacuum wall of a thermal/vacuum chamber will read higher than the actual pressure in a cold shroud

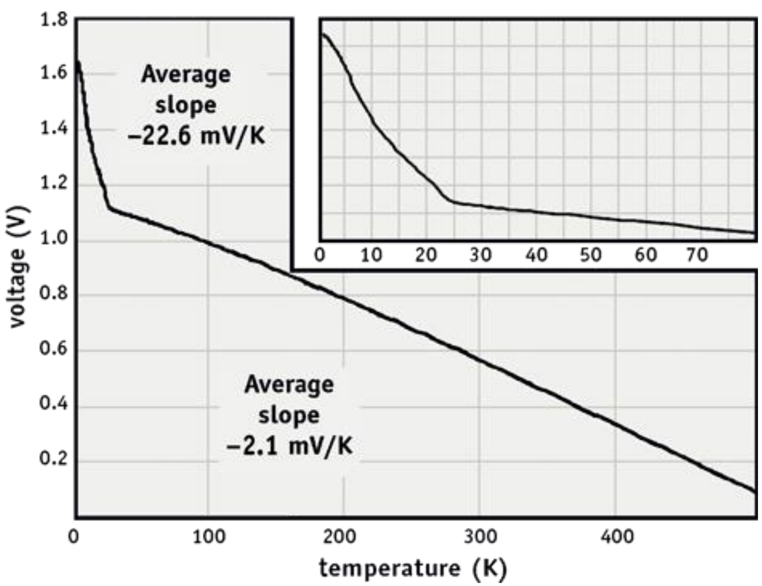
Thermometry

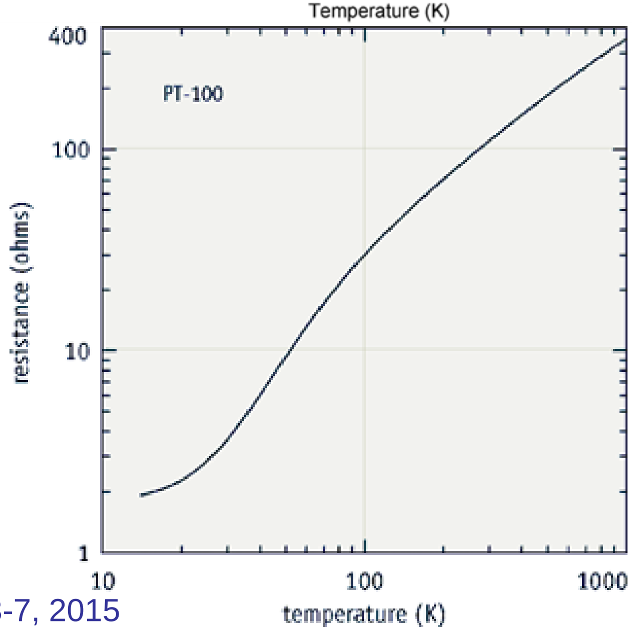
- Select thermometer type based on temperature range
  - Use 4 lead devices where high sensitivity and accuracy are required
    - Remove thermal emfs by reversing current
      - Not possible with diodes
- Self heating can produce erroneous readings in thermistors
  - Function of power and temperature
    - Readout power applied = 10^{-9} T^2
  - But, higher voltage can be used to obtain higher sensitivity at a cost of accuracy

Thermometry Chart

- Figure of merit for thermisters is 1/R•dR/dT
- Cernox – best < 70K
- Pt – best for > 70 K
- Si diodes good over wide range
- Thermocouples have very poor sensitivity below 100 K

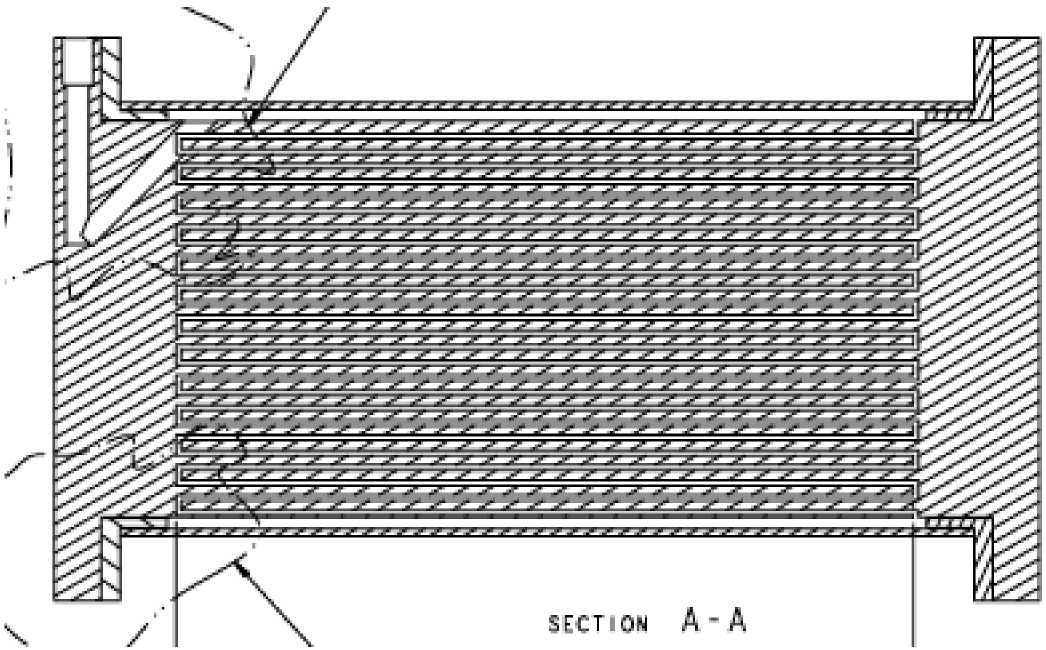






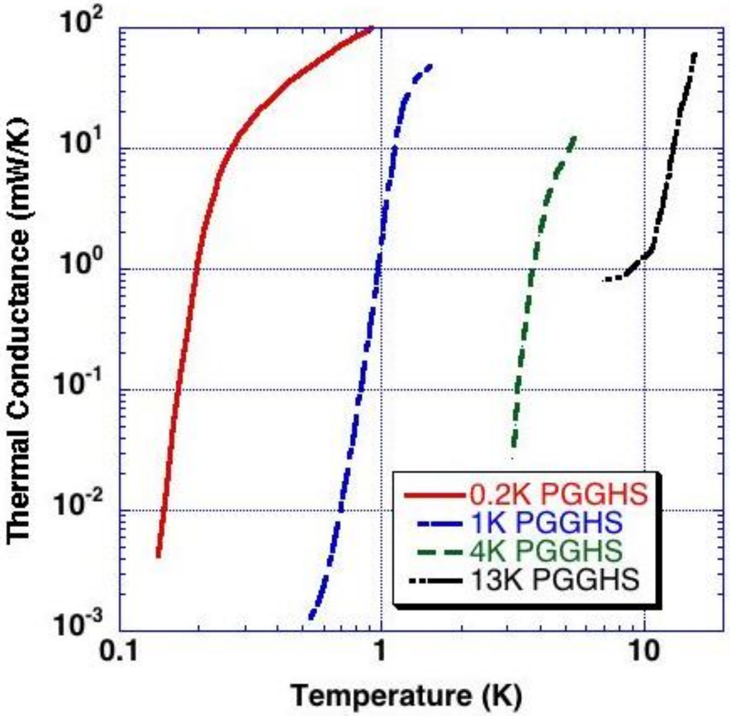
Heat Switches-Gas Gap

- Uses closely spaced conductors separated by thermally insulating material
- Gas is admitted to gap or pumped out by heating or cooling an adsorbing material (getter)



Heat Switches-Passive Gas Gap

- Passively Operated Gas Gap Heat Switch
  - Getter is thermally attached to the normally cold end

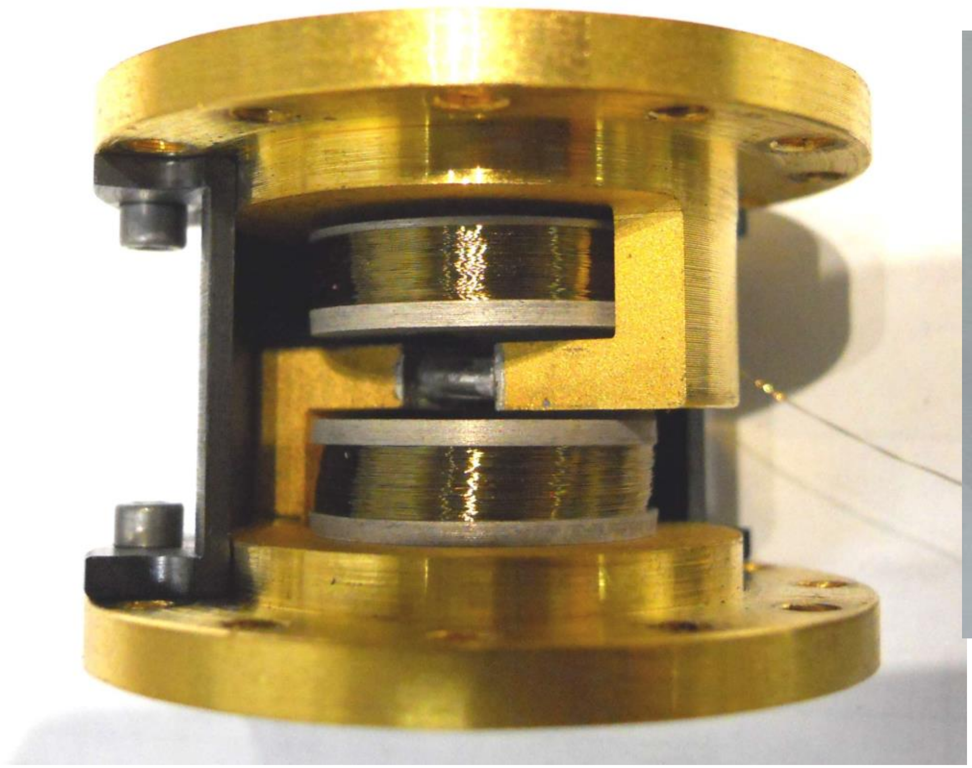


Heat Switches-Mechanical

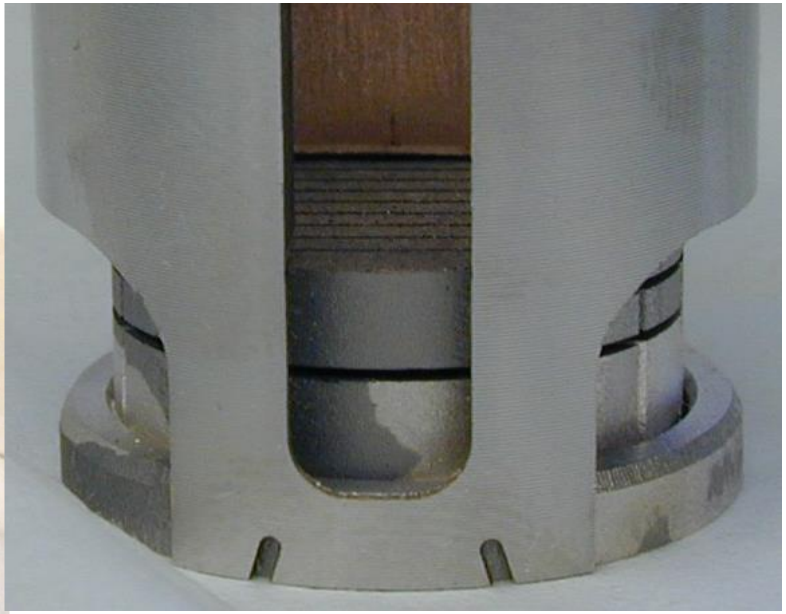
- Differential contraction
- Motor driven
- Manual
- Magnetostrictive
- Piezoelectric

Heat Switches - Other

Superconducting



Magnetoresistive



Superconductivity

- Quantum mechanical effect where electrons in certain conductors combine to form "Cooper pairs"
  - Transition point affected by temperature, current density, and magnetic field
- Characterized by zero electrical resistance and drop in thermal conductivity
  - Cooper pairs carry current and pass through the material without interacting
  - May be used for low T heat switch
- Types of superconductors
  - Type I – Generally pure metals, $T_c < 10$ K
    - Also can be used as a magnetic shield
  - Type II – Alloys, some pure metals, $T_c < 20$ K
    - Can remain superconducting in higher fields
  - MgB_2 – Magnesium Diboride, T_c ~39 K
  - High Temperature Superconductors (HTS) – Ceramics, $T_c < 110$ K

High Temperature Superconductivity

- Usually a ceramic consisting of RBCO, where R is a rare earth element, for instance YBCO, yttrium barium copper oxide
- Can make large/high field coils
- Joints have small amount of resistance so coil is not “persistent”
- Best performance is for bulk or flat tapes made with a thin film deposition
  - Round wire forms are now being explored

Making Use of Superconductivity

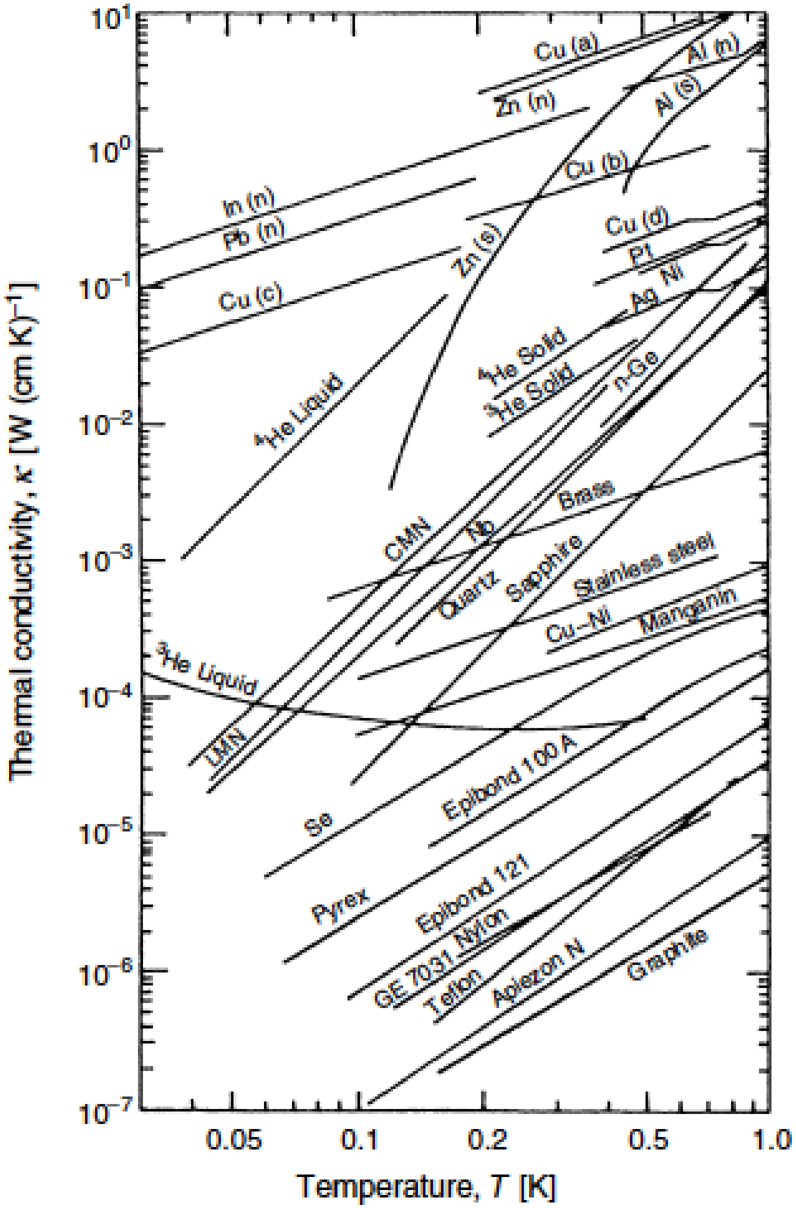
- i^2R-free coils for motors and actuators
  - Also proposed for energy storage
- Low thermal conductance high current wiring
- SQUIDs (Superconducting Quantum Interference Devices)

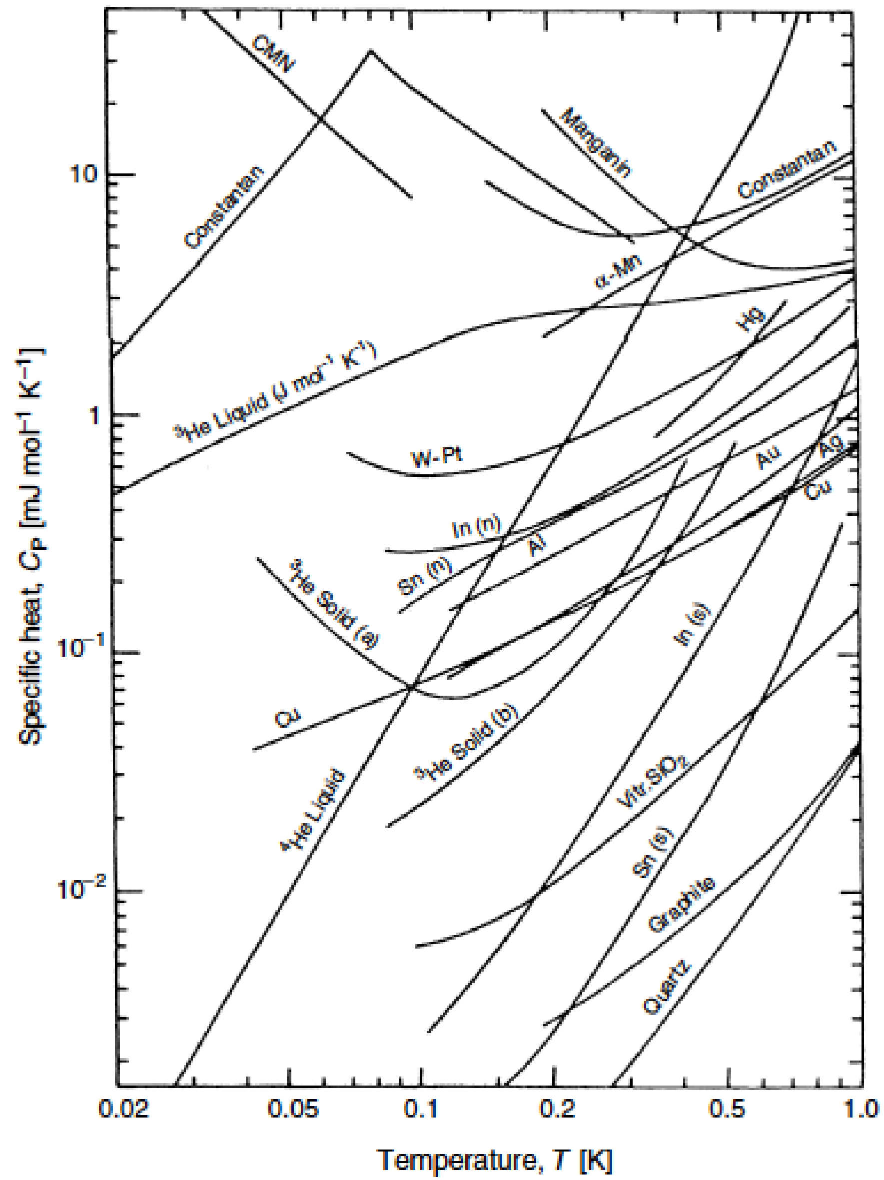
Magnet that produces 3 T with 2 A input

In the Regime of Sub Kelvin Temperatures

- Quantum behavior
  - ^3He has Fermi-Dirac statistics (like electrons) and ^4He has Bose-Einstein statistics (like photons)
  - Helium does not freeze at atm. pressure
- ^3He and ^4He
  - ^3He dissolves in ^4He, creating an opportunity for cooling
- Boundary resistance
  - Not thermal contact *per se*, but a thermal conductance that depends only on surface area
  - Due to phonon mismatch across two different solids or phonon mismatch from liquid helium to solid (Kapitza resistance)

Very Low T Conductivity and Specific Heat



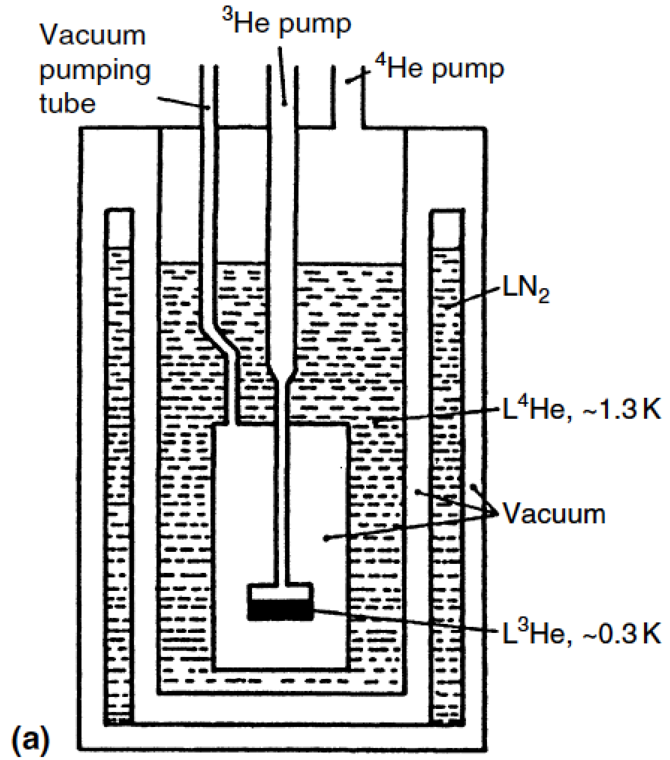


Sub Kelvin Refrigeration

- ^3He sorption coolers
- Dilution refrigerators
- Adiabatic demagnetization

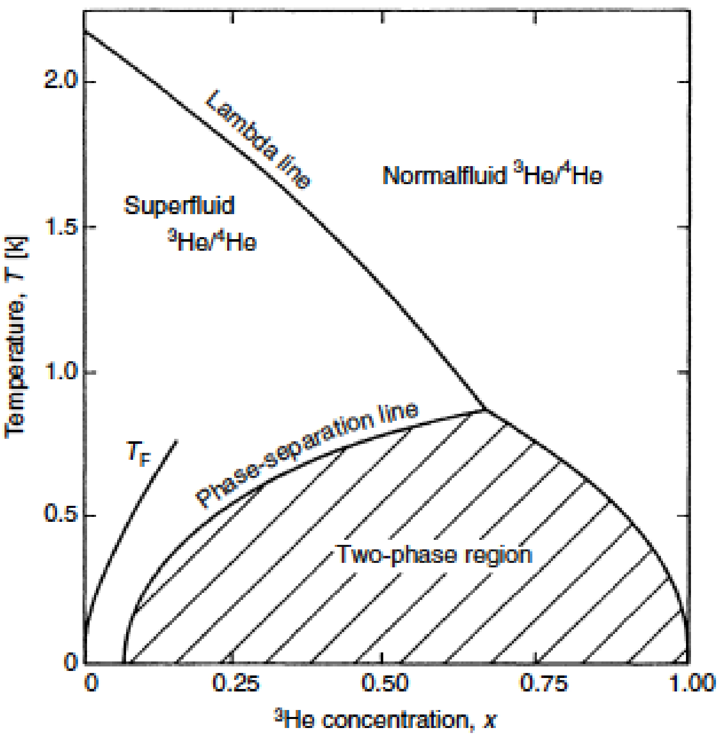
^3He Sorption

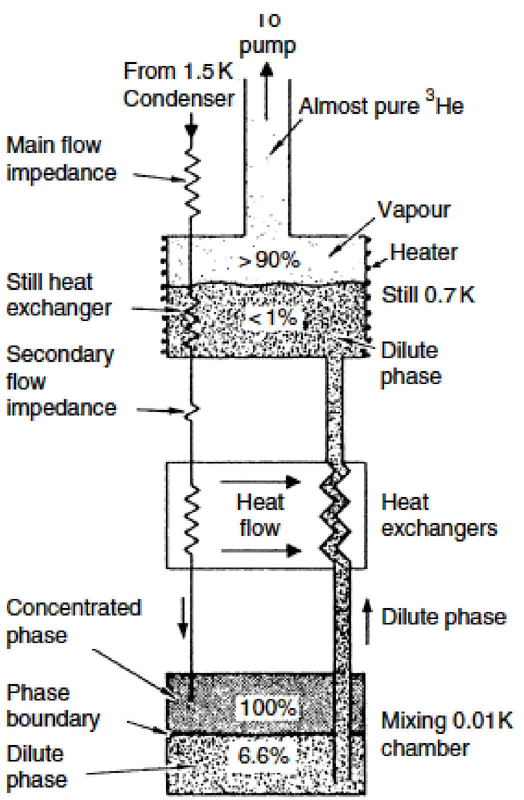
- Sorption Coolers use a getter to pump the vapor from a liquid reservoir
  - Getter is recycled by heating and the gas is recondensed by a higher temperature stage



Dilution Refrigeration

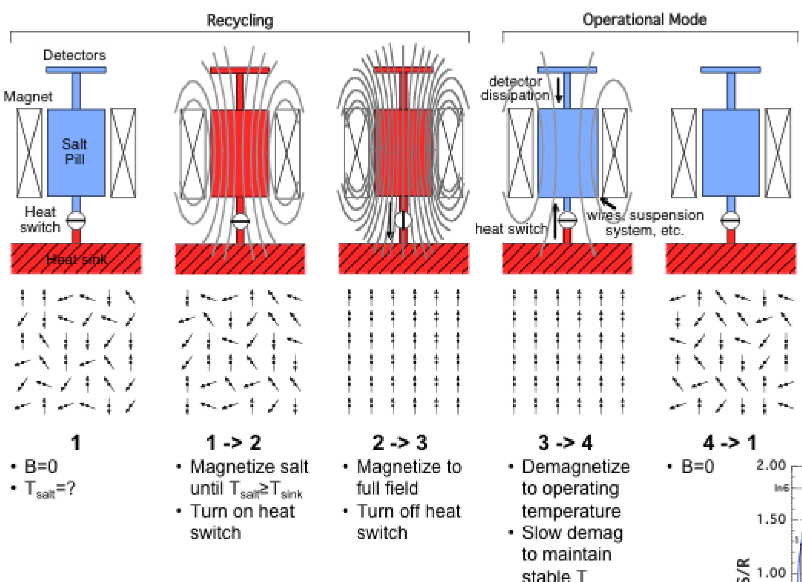
- Diluting the lighter isotope ^3He, in liquid ^4He, increases the entropy of the system and therefore cools
- Makes use of the non-zero solubility of ^3He in ^4He even at very low temperatures
- Can be made continuous by separating the ^3He out of solution at higher temperature and then re-condensing it

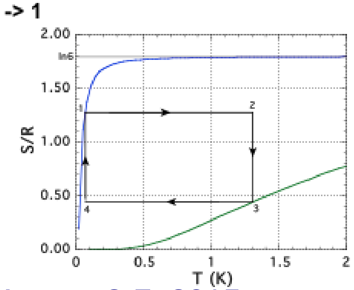




Adiabatic Demagnetization

- SdT = MdH takes the place of d(ST) = d(PV) in a cryocooler cycle
- [add in ch. 14 material from Zemansky]
- Adiabatic demagnetization refrigeration follows a very Carnot-like cycle of constant S and constant T
  - Produces efficiencies close to Carnot
  - No moving parts for low temperature ADRs using gas-gap heat switches





Continuous ADR

Biliography

- Spacecraft Thermal Control Handbook, Vol. II Cryogenics, Martin Donabedian, Ed., Aerospace Press (2003)
- Cryogenic Engineering, Thomas M. Flynn, CRC Press (2005)

Final Thought

- It has been said that a problem in low temperature physics can eventually be used to measure and achieve even lower temperatures
  - Problems are actually opportunities!